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A new perspective on total factor productivity differences

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Abstract

This paper investigates the relative contribution of capital deepening and total factor productivity (TFP) as drivers of labour productivity growth and catch up in Europe. Proxies for technological capabilities (technology gap) are introduced which allow to explain differences in TFP. Using a conditional Malmquist nonparametric approach, we find that capital deepening and TFP respectively account for around 53% and 47% of labour productivity growth respectively. Further, change in technological capabilities explains 71% of change in TFP, making a substantial contribution to catch up. Different patterns arise between industrialized and catching-up countries. Our results support the scope for innovation policy, technology diffusion and education policy to explain growth and convergence in labour productivity across Europe.

JEL classification: E23; O33; O47

Key words: labour productivity growth, technological capabilities, EU policies, Malmquist TFP

1. Introduction

Convergence in labour productivity (output per worker) is a key dynamic condition for European Union (EU) economic integration. A considerable exogenous shock (such as the current global turmoil) has demonstrated to bear different consequences across countries with different levels of labour productivity. Moreover the EU cohesion is based on the assumption that lagging behind countries will gradually catch up the more advanced countries in per capita income in the long run. This is reinforced by the fact that: (i) several countries have recently joined the EU as a result of the enlargement process, and (ii) four countries are currently candidates to join the EU in the coming years. This is very likely to exacerbate intra-EU economic differences. In fact, both these groups of countries are lagging behind in terms of income per capita and labour productivity. Figure 1 provides some impressionist evidence that an overall process of convergence in labour productivity has been occurring for the considered twenty-nine European countries relative to the period 1993-2007. That is, lagging behind countries seem to be catching up the more advanced EU Member states in terms of labour productivity. This paper investigates the drivers of this process.

[FIGURE 1]

Some studies point to capital deepening as an explanatory variable for differences in labour productivity (Kumar and Russell, 2002). Others argue that total factor productivity (TFP), in opposition to factor accumulation, plays a crucial role in bringing about productivity disparities (see among others Easterly and Levin, 2001; Jerzmanowski, 2007; Kutan and Yigit, 2007). We decompose labour productivity growth into capital deepening and (gross) TFP growth. Then, we further decompose (gross) TFP introducing proxies for technological capabilities (technology gap). Therefore TFP growth is decomposed into (i) net TFP (catching-up and exogenous technical change), and (ii) change in technological capabilities. While capital deepening and TFP have been largely addressed in this stream of research, technological capabilities have been quite underestimated. Our empirical results show that the omission of variables proxing for technological capabilities returns a different picture in terms of contribution to growth and TFP disparities.

The concept of technological capabilities has been put forward to explain the success of the South Asian countries to catch-up thanks to their capacity to attract and absorb technology developed abroad (Kim, 1980). Lately, technological capabilities have been more broadly conceptualized as a set of necessary capabilities for countries to master technology from the perspective of external adoption and internal generation of technology and innovation (Goto and Suzuki, 1989; Kogut and Chang, 1991; Lall, 1992). This stream of research is conceptually linked to the notion of absorptive capacity where the idea is that a country needs to have a certain type and level of knowledge and skills to successfully adopt foreign technology. Scholars have investigated both the role of human capital (Nelson and

Phelps, 1966), R&D capacity (Cohen and Levinthal, 1989), and institutions (Benson Durham, 2004) in facilitating the adoption of new technology in firms and countries (for a review see Keller, 2004). We follow Bell and Pavitt (1993) who regard technological capabilities as *a pre-condition for countries to generate and manage technical change,* both in terms of the introduction of new technology and innovation, as well as the incremental improvements of existing productive capacity. As such, they play a twofold role: their development is necessary for advanced countries to generate close-to-the-frontier technology, while as far as catching up countries are concerned, they are key to adopt technology and benefit from international technology diffusion (Cohen and Levinthal, 1990; Keller, 2004). In this sense, technological capabilities seem to be relevant whichever the distance of countries from the technological frontier. The set and combination of technological capabilities will vary depending on the stage of development of a country and on its specific industrial structure. We therefore take into consideration four different dimensions, customary in this literature, to account for technological capabilities: (i) innovation capability; (ii) codified knowledge; (iii) education; and (iv) labour force skills.[1]

The convergence versus divergence argument has been central to the European integration debate since the very beginning. During the 1970s the Community regional policy, inspired by the hypotheses of Gunnar Myrdal (1957), tried to counter-balance the agglomeration of capital and human resources towards the more developed regions at the expense of the peripheral ones. Both the Structural Funds and later the Cohesion Fund were grounded on the non-convergence hypothesis and therefore aimed to compensate regions that were lagging behind due to the asymmetric effects of integration (Leonardi, 1995; Boldrin et al., 2001). Several empirical studies have already addressed convergence and catch up in productivity in Europe (see among others Martin, 2001; Giannetti, 2002; Kutan and Yigit, 2007; Neven and Gouymte, 2008; Rodriguez-Pose and Crescenzi, 2008). This paper builds on those results and provides some further contributions. First, the dataset is updated to 2007 and includes a larger number of European countries to account for the recent enlargement process. Specifically, the EU New Member States (NMS) have been included along with three Candidate countries (CCs).[2] This allows investigating the current patterns of labour productivity in the light of the recent process of European enlargement. Second (as mentioned above), we introduce the role of technological capabilities to explain labour productivity growth and cross-country differences in TFP. Two main arguments have been proposed to explain differences in TFP. Some scholars argue that differences in TFP are due to inefficiency (*efficiency explanation)*, while others propose an alternative explanation according to which countries tend to be efficient but not all the existing technology can be adapted in their economy *(appropriate technology explanation)* (Basu and Weil, 1998; Acemoglu and

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[1] Another important factor is usually infrastructure. However, in our analysis infrastructure is accounted for by capital.

[2] The NMS include: Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Hungary, Poland, Romania, and Slovak Republic. The CCs include: Croatia, Island, and Turkey. We could not include Macedonia due to a lack of data. Also Cyprus and Malta have not been included in the empirical analysis.

Zilibotti, 2001; Los and Timmer, 2005; Jerzmanowski, 2007). In this paper we put forward a more general model accounting for both these explanations. To accomplish this task, we provide a modified version of the Malmquist nonparametric production model that is able to account for the relative contribution of the three factors (capital deepening, TFP and technological capabilities) under mild assumptions on the axiomatic production technology (Fare et al., 1994; Kumar and Russell, 2002; Jerzmanowski, 2007). The model is flexible enough to accommodate previous modelling strategies as special cases, thus providing a rationale base for the confrontation of alternative explanations of productivity patterns. Due to its nonparametric nature this approach accommodates cross-countries heterogeneity which has been recognized as a major problem when addressing convergence using standard parametric cross-country regression models (Durlauf et al., 2005).

Moving to the empirical results, we find that, for Europe as an average, capital deepening and TFP respectively account for around 53% and 47% of labour productivity growth. By further decomposing TFP we find that change in technological capabilities explains 71% of change in TFP, thus accounting for 33% of labour productivity growth. The catch up component, along with the technological capabilities is prominent among lagging behind countries. These results are discussed in relation to other pervious studies in the conclusions. The remaining of the paper is organised as follows. The next section reviews the debate on TFP differences and explains our contribution. Section 3 presents the data and describes the methodological strategy, while empirical results are discussed in Section 4. A summary of the key findings and policy implications are discussed in the last section.

2. Differences in total factor productivity: the state of the art and our contribution

Recently there has been a resurgence of interest in cross-country differences in aggregate productivity (Hall and Jones, 1999; Acemoglu and Zilibotti, 2001; Kumar and Russell, 2002; Kumbhakar and Wang, 2005; Jerzmanowski, 2007). Several contributions point to the role played by total factor productivity (TFP) (Hall and Jones, 1999; Easterly and Levin, 2001; Caselli, 2005). Easterly and Levin (2001) conclude that "the residual (TFP) rather than factor accumulation accounts for most of the income and growth differences across nations". However, as pointed out by Jerzmanowski (2007) "*these studies uncover only the proximate cause of income differences, in the sense that the ultimate cause are those that lead to different levels of inputs and productivity*" (p. 2081).

Two main arguments have been put forward to explain these disparities. Some scholars argue that differences in TFP are due to inefficiency (efficiency explanation). That is, while all the countries face the same technological frontier, the observed differences reflect a distance of countries from the frontier. An alternative explanation maintains that countries tend to chose their best technology mix (i.e. they are efficient), but not all the existing technology can be adapted in their economy (appropriate technology explanation) (Basu and Weil, 1998; Acemoglu and Zilibotti, 2001; Los and Timmer, 2005). In their model, Acemoglu and Zilibotti (2001) show that technologies invented by rich countries are not suitable for poor countries due to a different mix of input (e.g. skilled labor, machines). This leads to differences in incomes levels and a lack of convergence between poor and rich countries. Other studies point to the role of (or the lack of) institutions to account for differences in the capacity of countries in using efficiently technologies (Parente and Prescott, 1994; Krusel and Rios-Rull, 1996). The importance of efficiency vs. appropriate technology has been addressed in a comprehensive paper by Jerzmanowski (2007). He finds that efficiency appears to be the main explanation for low income countries explaining 43% of output variation across 79 countries, with appropriate technology accounting for a lower share.

This paper develops an empirical modeling which is compatible both with the efficiency explanation and the appropriate technology explanation. Figure 2 shows the functioning of these two explanations within a static context of technological frontier comparing country *a* and country *b* (with different levels of capital per worker). According to the efficiency explanation (left chart) all the countries face the same technological frontier. Countries below the frontier are *inefficient* while those onto the technological frontier are efficient. In this framework, the distance from the frontier reflects inefficiency that is entirely due to TFP. According to the appropriate technology explanation (right chart), each country faces a different technological frontier, but every country is perfectly efficient, i.e. lies on its frontier. In this context, country *a* cannot reach the upward frontier due to its endowment of inputs, i.e. technology and human capital.

[FIGURE 2]

Figure 3 summarizes our more general explanation. There are two different types of frontiers to be considered: the *unconditional* frontier (3) and the *conditional* frontier (1). The first is build as an external envelop of efficient points using the DEA. It hence represents the locus of the efficient countries at each point in time. The second is the frontier that each country faces *conditional* to its level of technological capabilities at each point in time (we call the technological capabilities variable "the Z's"). In this setting the distance to the unconditional frontier (which we define *gross* TFP) is decomposed into two factors: *net* TFP and technology gap (the Z's). Therefore, inefficiency is accounted for by the distance of country *a* to its *conditional* frontier, while the distance between the conditional frontier and the unconditional frontier is captured by the levels of the Z's. In this sense, our case is more general than the efficiency explanation or the appropriate technology explanation. In fact, both of them are special cases of our setting. On the one hand, if all countries have the same level of Z (our technological capabilities variable) would follow that: (i) all countries are facing the same conditional technological frontier (and this would collapse to the unconditional frontier), and (ii) differences in TFP are accounted for entirely by differences in efficiency (net TFP). On the other hand, if all the countries are efficient, they would all lie on their conditional technological frontier and all the differences in gross TFP would be entirely contingent upon differences in the levels of technological capabilities.

[FIGURE 3]

3. Data and methodology

Data

Table 1 summarizes the data collected for the empirical analysis. GDP is at constant prices and deflated by PPP's. GDP per worker is our dependent variable, and represents a standard measure for labour productivity (see Kumar and Russell, 2002 among others). The stock of capital has been built using the permanent inventory method[3]. Labour is measured as the number of people employed. Four variables have been collected in order to account for technological capabilities. Patent is a standard measure of innovation output and has been broadly used in order to measure innovation performance of countries (Griliches, 1990; Trajtenberg, 1990). As such, they can be considered a "tolerable assumption" (Schmookler, 1962) of the innovative activities of firms. The variable "scientific and technical articles" represents the magnitude of the generation of codified knowledge and has been often used in composite indicators addressing technological capabilities (Archibugi and Coco, 2004). Specifically, it reflects the knowledge generated in the universities and public-funded research centres. We take it as a proxy of the wealth of the research system. Finally, public expenditure in education and labour force with tertiary education account for investment in the education system and the skill of the work force.[4] We found these variables to be very volatile and decided to smooth them using the exponential moving average procedure.

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[3] The permanent inventory method is a quite standard tool to build a capital stock series from an investment series. See, for example, Hall, R. E. and Jones, C. I., 1999. Why so some countries produce so much more output per worker than other do The Quarterly Journal of Economics 114 (1), 83-116.

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, Iyer, K. G., Rambaldi, A. N. and Tang, K. K., 2008. Efficiency externalities of trade and alternative forms of foreign investment in OECD countries. Journal of Applied Econometrics 23 749-766.

[4] Very often growth studies take secondary enrolment as a measure of education. Given the fact that we are dealing with advanced and emerging countries, we decided to take these two other variables to address the quality of human capital. In this way, education expenditure provides an overall measure of public investment in education, while labour force with tertiary education accounts for the observed upper level quality of the labour force. These have demonstrated to be the most important source of growth for these types of countries, see Lee, K. and Kim, B., 2009. Both institutions and

[TABLE 1]

The production model

This section presents our nonparametric model. We propose a model that can be considered as a general version of those put forward by the inefficiency explanation and the appropriate technology explanation. We consider GDP as the outcome of a production process where capital and labour represent the inputs. The four technological capabilities variables are treated as external variables that condition the production process (see for example Daraio and Simar, 2005). Therefore the production technology is conditional on the observed level of the four external variables ($\mathbf{Z} \in R^4$). The production set is given by all the possible combinations of capital and labour able to produce a given level of output (GDP), conditional on $\mathbf{Z} \in R^4$ at time t:

$$T(\mathbf{Z},t) = \{(Y,K,L) \in R_+^3 : (K,L)\, can\ produce\, Y,\, given\, \mathbf{Z}\ and\ t\} \qquad (1)$$

A functional representation for this axiomatic technology is provided by the conditional output distance function:

$$D_o(Y,K,L \mid \mathbf{Z},t) = \min_\theta \left\{ \theta > 0 : \left(\frac{Y}{\theta}, K, L \right) \in T(\mathbf{Z},t) \right\} \leq 1 \qquad (2)$$

where the output distance function is conditional on the value of the technological capabilities **Z**[5]. The previous specification means that our model accommodates two important phenomena: *first*, the possibility that a country is lagging behind with respect to the international production frontier (the inefficiency parameter θ); *second*, it incorporates explicitly the role of technological capabilities in the production model through the introduction of the conditioning variables **Z**. What these assumptions mean is that two countries with same level of capital and labour can produce very different output levels according to the level of their technological capabilities. We assume the following monotonicity conditions of the conditional output distance function:

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policies matter but differently for different income groups of countries: Determinants of long-run economic growth revisited World Development 37 (3), 533-549.

[5] Since our empirical application uses only one output (GDP), the technology can be equally well represented via a production function (although we choose the output distance function due to its generality): $Y = \theta \cdot F(K,L \mid \mathbf{Z},t)$, where $0 < \theta \leq 1$ is the inefficiency parameter. The production function can be derived directly by the output distance function as: $D_o(Y,K,L \mid \mathbf{Z},t) = \frac{Y}{F(K,L \mid \mathbf{Z},t)}$. In other words the output distance function is a measure of "loss" in output or a measure of distance from the production frontier.

1. Non-decreasing in output: $D_o(Y_0, K, L \mid \mathbf{Z}, t) \leq D_o(Y_1, K, L \mid \mathbf{Z}, t)$, $Y_0 \leq Y_1$;

2. Non-increasing in inputs: $D_o(Y, K_0, L_0 \mid \mathbf{Z}, t) \leq D_o(Y, K_1, L_1 \mid \mathbf{Z}, t)$, $K_0 \leq K_1$, $L_0 \leq L_1$;

3. Non-increasing in the external variables: $D_o(Y, K, L \mid \mathbf{Z}_0, t) \leq D_o(Y, K, L \mid \mathbf{Z}_1, t)$, $\mathbf{Z}_0 \leq \mathbf{Z}_1$.

Assumptions 1) and 2) are quite standard. The first one says that increasing the level of output for a given level of inputs does not decrease the value of the distance function, i.e. does not decrease the efficiency of production. The second assumes that increasing the level of inputs for a given level of output does not increase the distance function, i.e. does not increase the efficiency of production. The third assumption needs some more detailed explanation. We assume that the external variables have the same monotonicity behavior of the inputs, in other words increasing the value of these variables do not increase the value of the distance function. This means that larger values of these variables displace the production frontier upwards allowing a larger production for a given level of inputs. Such an assumption is quite reasonable if one thinks that these conditioning variables are proxies for the level of human capital and for the effort that a country puts into innovation activities. Finally we do not make assumptions on the behavior of time; this means that when time passes the value of the distance function can increase (technical progress) or decrease (technical regress). It should also be stressed that our nonparametric model accommodates biased technical change, i.e. we do not assume Hicks neutrality (or any other type of neutrality) in technical change. Moreover, technical change is country specific, meaning that at different points of the production technology there could be different magnitudes and biases of technical change. Following standard practice in the macroeconomic literature constant returns to scale (CRS) are assumed. With the previous assumptions in place, the output distance function is homogeneous of degree one in output and homogeneous of degree -1 in inputs (Fare and Primont, 1995). The production set (1) is conditional to the value of the Z's variables. Omitting the Z's one obtains an unconditional or unrestricted production set:

$$T(t) = \{(Y, K, L) \in R_+^3 : (K, L)\, can\ produce\ Y,\ given\ t\} \qquad (3)$$

Since we use a DEA approach it is easy to verify that $T(t) \supseteq T(\mathbf{Z}, t)$ which means that the Z's are constraining production. The unconditional output distance function associated to the unconditional production set (3) will thus depend only on the output and inputs (the Z's are omitted):

$$D_o(Y, K, L) = \min_{\theta}\left\{\theta > 0 : \left(\frac{Y}{\theta}, K, L\right) \in T\right\} \leq 1 \qquad (4)$$

Following Daraio and Simar (2005), a comparison of the conditional distance function (2) to the unconditional distance function (4) gives a static measure of the magnitude of the impact of the Z-variables onto the production process:

$$ZC(\mathbf{Z},t \mid Y,K,L) = \frac{D_o(Y,K,L)}{D_o(Y,K,L \mid \mathbf{Z},t)} \qquad (5)$$

Since ZC belongs to the unitary interval, the Z-conditional production frontier (1) collapse to the unconditional production frontier (3) when the level of technological capabilities is not binding production (i.e., ZC=1). In other words equation (5) provides a measure of the distance between the conditional and the unconditional frontier (or, in other words, a measure of the technology gap).

The measure we provided in equation (5) is intrinsically static and it gives information on the technological capabilities gap at any point in time. A dynamic measure can be obtained very easily. A total factor productivity index can be defined keeping the technology fixed at the base period level and allowing the other variables to move (see, for example, Fare et al, 1994). This returns the Malmquist base period measure of total factor productivity growth:

$$TFP^t = \frac{D_o\left(Y^{t+1},K^{t+1},L^{t+1} \mid \mathbf{Z}^{t+1},t\right)}{D_o\left(Y^t,K^t,L^t \mid \mathbf{Z}^t,t\right)} \qquad (6)$$

Similarly, one can fix the technology to the comparison period level, obtaining a comparison period measure of productivity growth:

$$TFP^{t+1} = \frac{D_o\left(Y^{t+1},K^{t+1},L^{t+1} \mid \mathbf{Z}^{t+1},t+1\right)}{D_o\left(Y^t,K^t,L^t \mid \mathbf{Z}^t,t+1\right)} \qquad (7)$$

Taking the geometric mean, we obtain a Malmquist index of total factor productivity growth:

$$TFP = \left[TFP^{t+1} TFP^t\right]^{\frac{1}{2}} \qquad (8)$$

This index has been introduced by Caves et al. (1982), popularized by Fare et al (1994) and more recently applied by Kumar and Russell (2002) and Jerzmanowski (2007) with growth accounting decompositions purposes. It should be noted that, contrary to these previous studies (which use unconditional production frontiers), our productivity measure is conditioned by time and by the Z-variables. This means that observations with different Z-variables face different production frontiers and the productivity index account for that. This productivity measure decomposes into two different components. First, a measure of catching-up (TEC):

$$TEC = \frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1} \mid \mathbf{Z}^{t+1}, t+1\right)}{D_o\left(Y^{t}, K^{t}, L^{t} \mid \mathbf{Z}^{t}, t\right)} \qquad (9)$$

Since our model allows deviations from the production frontier this index account for the trend in this deviation. A value of TEC larger than one means that the country has moved closer to the conditional production frontier (catching-up), while a value smaller than one means that the country is falling behind with reference to the conditional production frontier. The second component of TFP is a measure of exogenous technical change (TC) and it can be obtained into two different ways. The base period index of local technical change is:

$$TC^{t} = \frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1} \mid \mathbf{Z}^{t+1}, t\right)}{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1} \mid \mathbf{Z}^{t+1}, t+1\right)} \qquad (10)$$

while the comparison period local technical change index is:

$$TC^{t+1} = \frac{D_o\left(Y^{t}, K^{t}, L^{t} \mid \mathbf{Z}^{t}, t\right)}{D_o\left(Y^{t}, K^{t}, L^{t} \mid \mathbf{Z}^{t}, t+1\right)} \qquad (11)$$

The geometric mean of these two procedures avoids the arbitrariness of choosing one procedure instead of the other:

$$TC = \left(TC^{t} TC^{t+1}\right)^{\frac{1}{2}} \qquad (12)$$

This index gives a measure of local technical change, with values larger than one for technical progress and values smaller than one for technical regress. It is easy to verify that the product of the TEC component by the TC component returns the original Malmquist TFP index:

$$TFP = TC \cdot TEC \qquad (13)$$

The Malmquist index defines a net measure of productivity change. Since the Z’s are constraining production, their variation displaces the conditional frontier closer or farther to the unconditional frontier. Therefore the contribution of the Z’s can be accounted for by the following index that quantifies the impact of technological capabilities (ZCC) onto labour productivity:

$$ZCC^{t} = \frac{D_o\left(Y^{t}, K^{t}, L^{t} \mid \mathbf{Z}^{t}, t\right)}{D_o\left(Y^{t}, K^{t}, L^{t}, t\right)} \frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1}, t\right)}{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1} \mid \mathbf{Z}^{t+1}, t\right)} \qquad (14)$$

This index accounts for the variation in the $ZC(Y,K,L\mid \mathbf{Z},t)$ function of equation (5) and it is a measure of the impact of Z's. To be precise, it should be noted that this index is composed by two sub-components. The first represents the "pure" effect of the Z's:

$$\frac{D_o\left(Y^t,K^t,L^t\mid \mathbf{Z}^t,t\right)}{D_o\left(Y^t,K^t,L^t\mid \mathbf{Z}^{t+1},t\right)}$$

This index take a value equal to one if $\mathbf{Z}^t=\mathbf{Z}^{t+1}$ and different from one if $\mathbf{Z}^t\neq\mathbf{Z}^{t+1}$. In this second event the index will be larger than one if the overall impact of the change in technological capabilities has been positive and smaller than one otherwise. The other sub-component is an interaction effect between the factors of production and the technological capabilities:

$$\frac{D_o\left(Y^t,K^t,L^t\mid \mathbf{Z}^{t+1},t\right)}{D_o\left(Y^t,K^t,L^t,t\right)}\frac{D_o\left(Y^{t+1},K^{t+1},L^{t+1},t\right)}{D_o\left(Y^{t+1},K^{t+1},L^{t+1}\mid \mathbf{Z}^{t+1},t\right)}$$

To avoid the complexities associated to such a sub-decomposition, we will consider only index (14) which incorporates both the "pure" effect of the Z's and their interaction effect with the factors of production. An alternative index for the impact of technological capabilities is the comparison period one:

$$ZCC^{t+1}=\frac{D_o\left(Y^t,K^t,L^t\mid \mathbf{Z}^t,t+1\right)}{D_o\left(Y^t,K^t,L^t,t+1\right)}\frac{D_o\left(Y^{t+1},K^{t+1},L^{t+1},t+1\right)}{D_o\left(Y^{t+1},K^{t+1},L^{t+1}\mid \mathbf{Z}^{t+1},t+1\right)} \qquad (15)$$

To avoid the arbitrariness of choosing one index rather than the other, we compute a geometric mean index for the impact of technological capabilities onto output per worker growth:

$$ZCC=\left(ZCC^t ZCC^{t+1}\right)^{\frac{1}{2}} \qquad (16)$$

Finally, one can account for the effect of capital deepening considering a base and a comparison period index:

$$KD^t=\frac{L^t}{L^{t+1}}\frac{D_o\left(Y^t,K^t,L^t\mid t\right)}{D_o\left(Y^t,K^{t+1},L^{t+1}\mid t\right)}=\frac{D_o\left(y^t,k^t,1\mid t\right)}{D_o\left(y^t,k^{t+1},1\mid t\right)} \qquad (17)$$

$$KD^{t+1}=\frac{L^t}{L^{t+1}}\frac{D_o\left(Y^{t+1},K^t,L^t\mid t+1\right)}{D_o\left(Y^{t+1},K^{t+1},L^{t+1}\mid t+1\right)}=\frac{D_o\left(y^{t+1},k^t,1\mid t+1\right)}{D_o\left(y^{t+1},k^{t+1},1\mid t+1\right)} \qquad (18)$$

Taking the geometric mean of the previous two components one obtains the capital deepening effect:

$$KD = \left(KD^{t} KD^{t+1}\right)^{\frac{1}{2}} \quad (19)$$

The product of the four components (TEC, TC, ZCC and KD) returns a decomposition of output per worker growth (growth accounting):

$$\frac{Y^{t+1}/L^{t+1}}{Y^{t}/L^{t}} = TEC \cdot TC \cdot ZCC \cdot KD = TFP \cdot ZCC \cdot KD \quad (20)$$

It is useful to provide an additional graphical representation of the dynamic process. In figure 4 two hypothetical observations are represented: (y_t, k_t) facing technology $T(\mathbf{z}_t, t)$ and (y_{t+1}, k_{t+1}) facing technology $T(\mathbf{z}_{t+1}, t+1)$. The difference in output per worker ${y_{t+1}}/{y_t}$ can be ascribed to three different movements. First, keeping the technology fixed at $T(\mathbf{z}_t, t)$ we consider the impact of the capital deepening effect from point A to point B. Second, we account for the effect of technological capabilities considering the hypothetical technology $T(\mathbf{z}_{t+1}, t)$; thus the movement from point B to point C. Third we consider the contribution of total factor productivity growth, considering the movement from the hypothetical frontier $T(\mathbf{z}_{t+1}, t)$ to the observed frontier $T(\mathbf{z}_{t+1}, t+1)$; thus the movement from point C to point D. Summing-up, output per worker growth can be decomposed as: $\frac{y_{t+1}}{y_t} = \frac{y_B}{y_t}\frac{y_C}{y_B}\frac{y_{t+1}}{y_C} = KD \cdot ZCC \cdot TFP$.

[FIGURE 4]

Equation (20) is our growth accounting equation which imputes labour productivity growth to 4 different components: catching-up (or falling behind) effect (TEC), technological capabilities change (ZCC), exogenous technical change (TC) and capital deepening (KD). Since the contribution of ZCC enlarges the production technology it can be interpreted as a contributor to productivity growth. Our TFP component (8) is a net measure of productivity growth, therefore taking the product of TFP by ZCC returns a measure of gross productivity growth (GTFP):

$$GTFP = \left(\frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1}, t\right)}{D_o\left(Y^{t}, K^{t}, L^{t}, t\right)} \frac{D_o\left(Y^{t+1}, K^{t+1}, L^{t+1}, t+1\right)}{D_o\left(Y^{t}, K^{t}, L^{t}, t+1\right)} \right)^{\frac{1}{2}} \quad (21)$$

This returns a quite surprisingly simple result, i.e. given our assumptions gross productivity change can be computed simply omitting the Z variables from the production model. Since this is the way followed by the most part of authors, our methodology can be interpreted as a way of decomposing gross TFP, where gross TFP is measured as in the rest of the literature. In other words, our model generalizes previous models and maintains comparability. In fact, aggregating the TFP and ZCC components one obtains the Kumar and Russell (2002) and Jerzmanovsky (2007) growth accounting procedure:

$$\frac{Y^{t+1}/L^{t+1}}{Y^{t}/L^{t}} = TFP \cdot ZCC \cdot KD = GTFP \cdot KD \qquad (22)$$

where the only components are gross TFP growth and capital deepening. All the previous distance functions needed to compute the different indexes are estimated using DEA linear programs (see appendix B).

4. Empirical results

A picture of the unconditional production frontier is reported in figure 5. It is very clear from this picture that the shift in the production frontier is not neutral. In fact, the displacement at high values of capital per worker is much stronger than at low values. This means that countries with high levels of capital per worker benefited more from technical change and TFP growth. The result is in line with Kumar and Russell (2002), who also obtain a similar biased shift in the technological frontier.

[FIGURE 5]

Table 2 summarizes the results of our output per worker decomposition for all 29 countries. In a first step, labour productivity change has been decomposed into two main components: capital deepening and gross TFP change (columns 4 and 5). The overall averages provided in the last row suggest a similar contribution to the growth in labour productivity, with capital deepening accounting for 57% and gross TFP accounting for 43% of total growth. In a second step we decomposed gross TFP change in technological capabilities change (ZCC) and net TFP change (columns 6 and 7). It arises that the change in technological capabilities explains a good deal of the change in gross TFP (around 71%), thus accounting for 33% of overall labour productivity growth. The further decomposition of net TFP in catch-up effect (TEC) and exogenous technical change (TC) reported in the last two columns shows the significant role of the former vis-à-vis the negligible role of the latter.

[TABLE 2]

We have also divided the countries into two different groups. The EU-16 group includes the ‘old’ EU Member States, which are also the more industrialized countries. While the EU-13 group includes both the New Member States and the Candidate Countries (see note in table 2). The differences between the two groups are striking. As regards the EU-13, labour productivity growth has been substantially higher (4.5%) in opposition to the EU-16 (1.9%). As far as the relative contribution to labour productivity growth is concerned, capital deepening is similar for the two groups of countries (around 50% of total labour productivity growth), while significant differences emerge for technological capabilities and net TFP. The former accounts for 29% of total change in the EU-16 group, while it accounts for 38% of total change in the EU-13 group. Net TFP accounts for 19% and 10% relative to the EU-16 group and the EU-13 group respectively. A remarkable difference also arises from the decomposition of the net TFP. EU-16 countries benefited from exogenous technical change, while this has a negative role for EU-13 countries. By contrast, the latter considerably benefited from the catching up effect (TEC).

As mentioned in the previous section, the ratio in equation (5) of the unconditional distance function to the conditional distance function is a measure of the impact of the Z's on the production frontier (see Table A.1 in the Appendix). Lower values suggest a strong impact of the Z's, while values close to 1 reflect a moderate importance of the Z's (a value equal to 1 reflects countries where the unconditional frontier overlap with the conditional frontier). The overall average is 0.84 and very stable across years. On the contrary it varies considerably across countries. Figure 6 shows index (5) (static impact of the technological capabilities). Considerable differences emerge between the EU-16 and the EU-13,[6] which implies a more important role played by technological capabilities for the EU-13 countries.

Our model aims to generalize those provided by the efficiency explanation and appropriate technology explanation (cf. Figure 2, 3). As explained above, in our setting the Z's account for the appropriate technology explanation. The trends outlined in Figure 6 suggest that the appropriate technology explanation is prominent for catch-up countries while it plays a moderate role for advanced countries, consistently with Jerzmanowski (2007). Further, the upward trend of the EU-13 group suggests a relative lower importance as far as the EU-13 countries tend to catch up.

[FIGURE 6]

The next figure summarizes our calculations by plotting the change rates of the three components against output per worker in 1993, with simple regressions. By looking at the charts, the EU-13 countries seem to catch up both in terms of capital deepening and technological capabilities, while the contribute of gross TFP does not seem to make a significant contribution. Figure 7 reports the gross TFP decomposition into a catch-up component (TC) and an exogenous technical change component (TC). It shows that the TC component is an important factor of convergence while exogenous technical

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[6] One can dispute that Iceland is in fact a catch up country. Taking Iceland out would reinforce the results as the EU-13 line would shift slightly downward, but it would not affect the dynamic picture.

change tends to increase divergence. This basically explains why net TFP does not show a clear pattern.

[FIGURE 7]

[FIGURE 8]

Overall a convergence process in labour productivity growth can be ascribed to an interaction of factors. The EU-13 group shows, on average, a lower value of capital per worker and the catch-up process starts with a low level of efficiency, technological capabilities and capital per worker. Then, the convergence process seems to be lead by capital deepening, catch-up and technological capabilities accumulation in a first stage. Only when a country reaches a larger level of capital per worker is able to exploit the TFP change (due to the TC component) that happens at the higher level of capital per worker. It seems that, once this stage is reached, the static effect of technological capabilities (as proxied by our ZC index) turns out to be diminished.

It is worth commenting how different patterns of convergence arise also within the EU-13 group. Specifically, the three Baltic Republics – Latvia, Lithuania, and Estonia – show a different and specular pattern when compared to Romania, Bulgaria, and Hungary, even though they started at similar levels of labour productivity level in 1995 (cf. Figure 1). The former seem to have based their catch up process mainly on capital deepening in opposition to technological capabilities, while the opposite is true for the latter. Interestingly, these countries are also geographical clustered.

4. Discussion and concluding remarks

This paper investigates the source of growth and catch up of labour productivity in the current framework of EU enlargement, in the period 1993-2007. We propose a general model to merge the efficiency explanation and the appropriate technology explanation introduced previously in the literature to explain cross-country TFP differences. Variables proxing for the level of technological capabilities have been introduced to explain TFP differences across countries. To accomplish this task we follow a nonparametric production approach and Malmquist indexes decompositions. We start by pointing out an overall process of convergence in labour productivity occurred over the considered period relative to the 29 countries: lagging behind countries exhibit higher rates of labour productivity growth (4.5%) with respect to the more industrialized European countries (1.9%). Labour productivity growth is decomposed into three components: capital deepening, TFP change, and technological capabilities change. Further, TFP is decomposed into an exogenous technical change effect and a catching up effect.

For Europe as a whole, productivity growth is mostly driven by capital deepening and the change in accumulation of technological capabilities. By contrast, TFP does not seem to make a relevant contribution. Different patterns arise between industrialized and catching-up countries. As for the former, the accumulation of technological capabilities contributed in a more important way in opposition to TFP, which in turn is more prominent regarding industrialized countries (with technological capabilities playing a less important role). Our further decomposition of net TFP into exogenous technical change and a catch up component allowed us to single out additional differences between these two groups of countries. As for lagging behind countries, it arises a considerable catch-up effect while exogenous technical change has been negative. By contrast, industrialized countries benefited by far from exogenous technical change (this last component tends to exacerbate cross-country differences in labour productivity). This is consistent with a non-neutral shift of the technological frontier observed in our analysis (see figure 5) (for similar finding see Kumar and Russell, 2002), as well as with those arguments pointing to a lower capacity of countries distant from the frontier to master close-to-the-frontier technical change (Acemoglu and Zilibotti, 2001; Acemoglu et al., 2006). In brief, rich countries tend to generate technology that is not compatible with the factor mix of lagging behind countries.

Our results point to the importance of technological capabilities as an explanatory variable for cross-country differences in gross TFP. Once technological capabilities are included, the net TFP no longer show up as a key variable. Kumar and Russell (2002) find that growth was largely attributable to capital deepening, while (gross) TFP plays a negligible role. This difference can be ascribed to differences in the sample. In their paper the very low effect of TFP is due to larger negative figures for very low-income countries. In their study technology is only exogenous, as captured by the shift of the technological frontier. Moreover some key variables such as human capital are not included, as they recognized themselves. Their findings are in contrast with other several studies pointing to the importance of TFP instead of factor accumulation to explain cross-country differences in growth rates (Easterly and Levin, 2001). In a recent study Jerzmanowski (2007) shows the relative importance of the efficiency view and the appropriate technology view in explaining TFP differences. Within a customary Cobb-Douglas framework he provides evidence for both explanations.[7] Along a similar line, our results show that an important share of the contribution of gross TFP to productivity growth can be accounted for by the change in technological capabilities.

Our results need to be further qualified. Capital deepening has demonstrated to be as much as relevant as gross TFP in explaining productivity growth. This might seem at odds with studies showing that TFP accounts for the lion's share of productivity growth. However, this is not so surprising considering

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[7] He also shows that by relaxing the Cobb-Douglas assumption by using a DEA non parametric approach, consistent with that used in this paper, this method tends to give more importance to the fraction of variation of output explained by factor accumulation vis-à-vis TFP.

our specific sample. The latter includes emerging economies whose distance from the technological frontier can be by all means considered inferior to many developing countries usually included in the empirical studies discussed. This reduces their catch up opportunities and explains the greater importance attached to capital deepening and technological capabilities in our results. Moreover, many of the studies that find a large contribution of TFP might incur a specification error, since they adopt very restrictive functional forms (i.e. Cobb-Douglas) for the production frontier. This is likely to increase the effect of TFP versus factor accumulation (Jerzmanowski, 2007).

Summing up, this paper contributes in two ways to the current debate on the sources of cross-country differences in growth and productivity. First, it introduces the concept of technological capabilities as a means to explain cross-country differences in productivity growth and TFP. Second, in order to explore the efficiency explanation vs. appropriate technology explanation, it provides a more general methodological framework using a nonparametric production approach and Malmquist indexes decompositions.

Our empirical findings bear some consequences in terms of policy. NMS and CCs do not benefit from exogenous technical change and this suggests that economic integration *per se* is not a sufficient condition for lagging behind countries to catch-up. The opportunity for lagging behind countries to catch-up (and ultimately the cohesion of an enlarged Europe itself) cannot be grounded solely on automatic mechanisms such as spillover effects and capital going towards countries with lower levels of labour productivity. On the contrary, it rests on policies that point to a substantial endogenous effort in terms of innovation capabilities, education and research system, and skills of labour force.

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Appendix A – Figures and Tables

Fig. 1. Convergence in output per worker over the period 1993-2007, 29 European countries

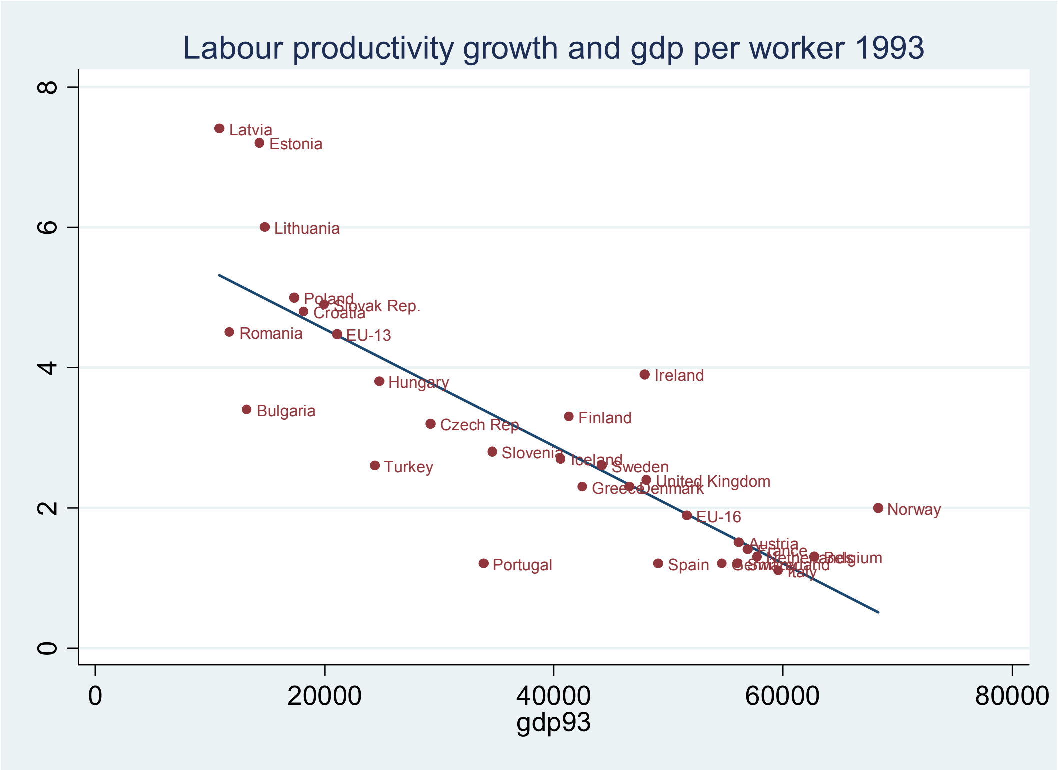


Fig.2. The efficiency explanation vs. the appropriate technology explanation

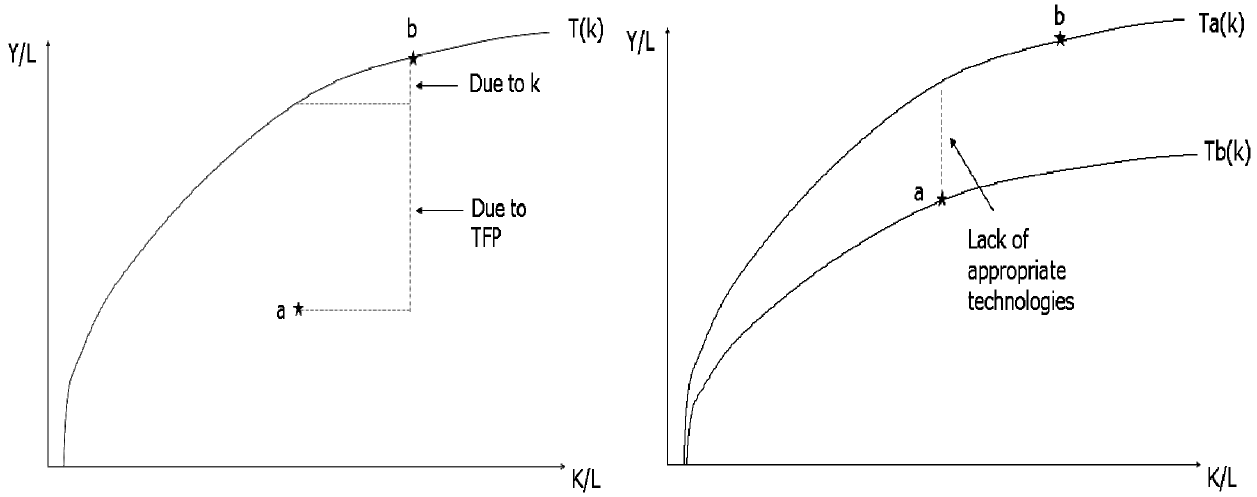


Fig. 3. The technological capabilities explanation

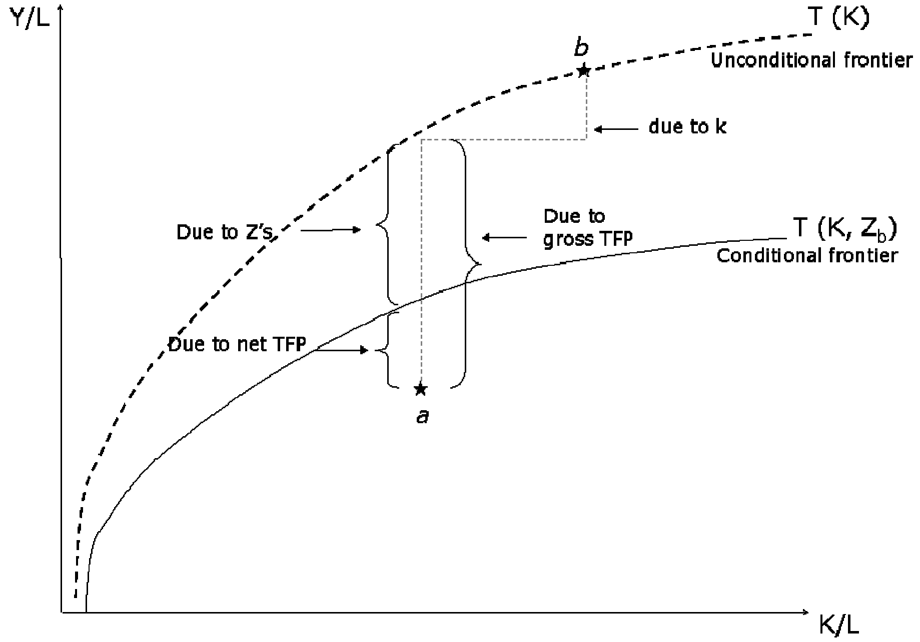


Table 1 - Variables and sources

	Variable	Sources
GDP per worker:	GDP (PPP, constant prices)	Penn World Table
measure of productivity (dependent variable)	Labour force	Penn World Table
Capital deepening	Fixed capital (build with the permanent inventory method)	Penn World Table
Technological capabilities accumulation (Z)	Patents application in the European Patent Office	OECDstat
	Articles published in scientific journals	WDI (World Bank)
	Public expenditure in education	WDI (World Bank)
	Labour force with tertiary education	WDI (World Bank)

Fig. 4. The decomposition of labor productivity over two time period

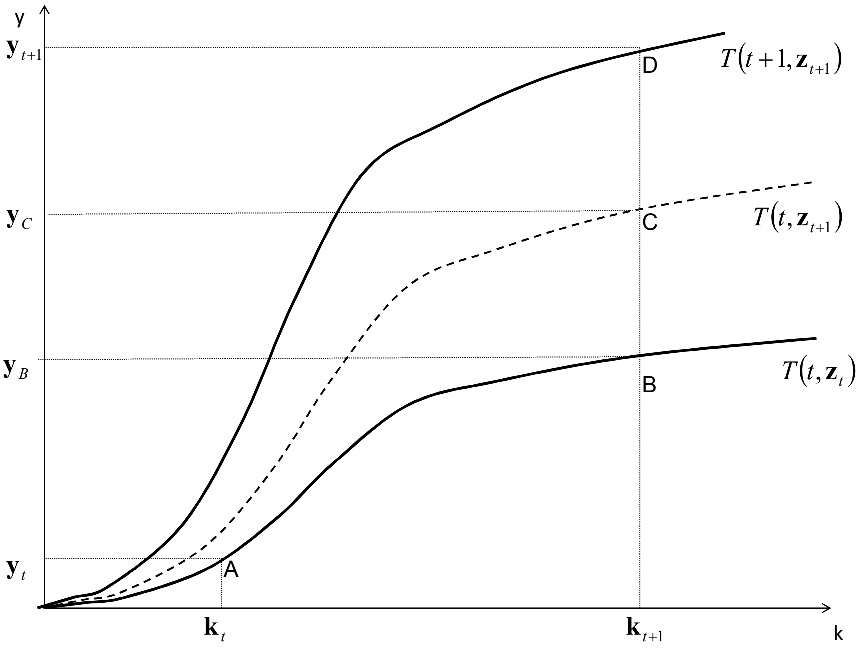


Fig. 5. The unconditional production frontier, 1993 and 2007.

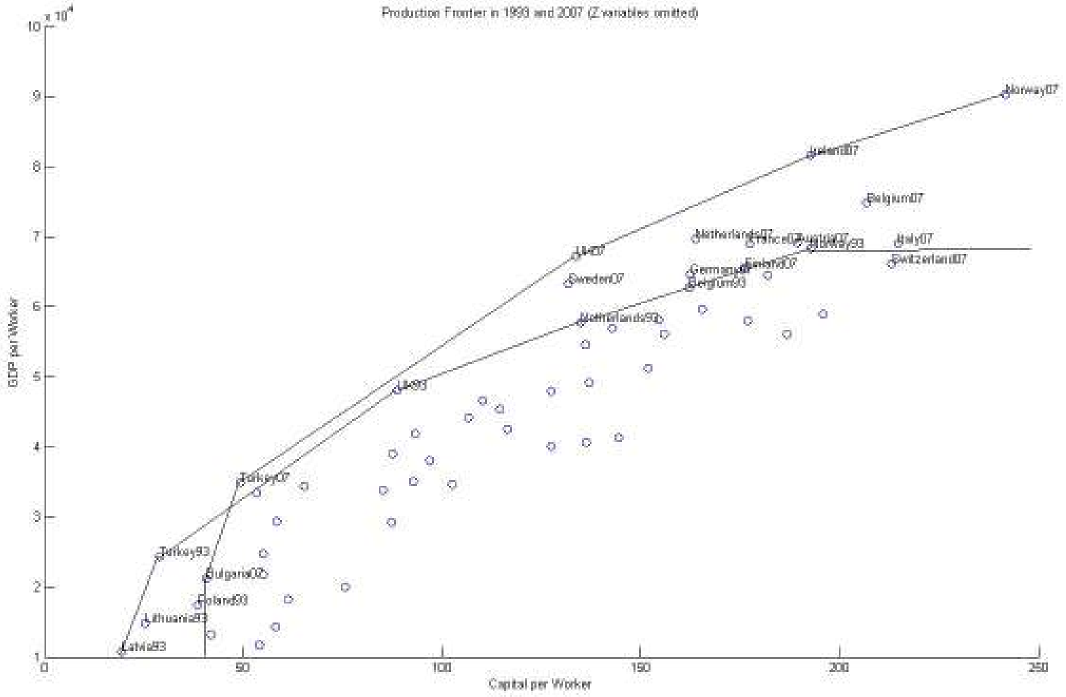


Table 2 - Percentage change of output per worker decomposition 1993-2007, 29 countries

				Contribution to change in GDP per worker					
						Gross TFP		Net TFP	
Country	GDP per Worker 1993 (1)	GDP per Worker 2007 (2)	Percentage GDP per Worker Growth (3)	Capital Deepening (4)	Gross TFP (5)	ZCC (6)	Net TFP (Malmquist) (7)	TEC (8)	TC (9)
Austria	56,143	69,138	1.5	0.7	0.8	0.9	-0.1	0.1	-0.3
Belgium	62,717	74,879	1.3	0.9	0.4	0.6	-0.2	-0.7	0.5
Bulgaria	13,230	21,187	3.4	0.4	3	6	-2.8	0	-2.8
Croatia	18,169	35,104	4.8	2.2	2.6	1.2	1.3	1.4	0
Czech Rep.	29,239	45,317	3.2	1.6	1.6	2.1	-0.5	0	-0.5
Denmark	46,606	64,478	2.3	1.8	0.6	0.3	0.3	-0.6	0.9
Estonia	14,320	38,007	7.2	2.7	4.4	1.2	3.1	3.4	-0.2
Finland	41,318	65,417	3.3	0.7	2.6	0.6	2	1.3	0.6
France	56,917	69,014	1.4	0.8	0.6	0.4	0.2	-0.7	0.9
Germany	54,660	64,692	1.2	0.6	0.6	0.7	-0.2	-0.1	-0.1
Greece	42,493	58,178	2.3	0.9	1.3	1.4	-0.1	0	-0.1
Hungary	24,740	41,848	3.8	2.9	0.9	-0.3	1.2	0.7	0.4
Iceland	40,616	58,945	2.7	1.3	1.3	-0.6	1.9	0.4	1.5
Ireland	47,928	81,673	3.9	1.5	2.4	-0.2	2.6	0.5	2.1
Italy	59,565	68,952	1.1	1	0.1	1.2	-1.1	0	-1.1
Latvia	10,806	29,298	7.4	7	0.4	-3.2	3.6	3	0.7
Lithuania	14,767	33,401	6	4.6	1.3	-0.4	1.7	2.6	-0.8
Netherlands	57,728	69,648	1.3	0.7	0.7	0.6	0.1	-0.3	0.4
Norway	68,289	90,345	2	0.4	1.6	0.5	1	0	1
Poland	17,360	34,310	5	2.5	2.4	1.4	1	2	-1
Portugal	33,849	40,070	1.2	1.7	-0.5	1	-1.5	-0.1	-1.4
Romania	11,695	21,700	4.5	0	4.5	6.8	-2.2	0	-2.2
Slovak Rep.	19,976	38,938	4.9	0.7	4.1	4.6	-0.4	1.7	-2.1
Slovenia	34,618	51,204	2.8	1.5	1.3	0.7	0.6	0.4	0.2
Spain	49,125	57,919	1.2	0.9	0.3	0.2	0.1	-0.7	0.8
Sweden	44,187	63,261	2.6	0.7	1.9	0.1	1.8	0.9	0.9
Switzerland	56,043	66,193	1.2	0.2	1	0.3	0.7	-0.4	1.1
Turkey	24,341	34,960	2.6	3.1	-0.4	2.4	-2.8	0	-2.8
United Kingdom	48,070	67,203	2.4	1.8	0.6	0.2	0.4	0	0.4
EU-16	*51,602*	*66,941*	*1.9*	*1.0*	*0.9*	*0.6*	*0.4*	*-0.1*	*0.4*
EU-13	*21,067*	*37,248*	*4.5*	*2.4*	*2.1*	*1.7*	*0.4*	*1.2*	*-0.7*
Overall Mean			***3.0***	***1.6***	***1.4***	***1.0***	***0.4***	***0.5***	***-0.1***

Note: EU-16 include the more industrialized countries; EU-13 include the NMS and CCs, namely Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Hungary, Poland, Romania, and Slovak Republic. The CCs include: Croatia, Island, and Turkey

Fig.6. The impact of the technological capabilities on the production frontier, overall averages

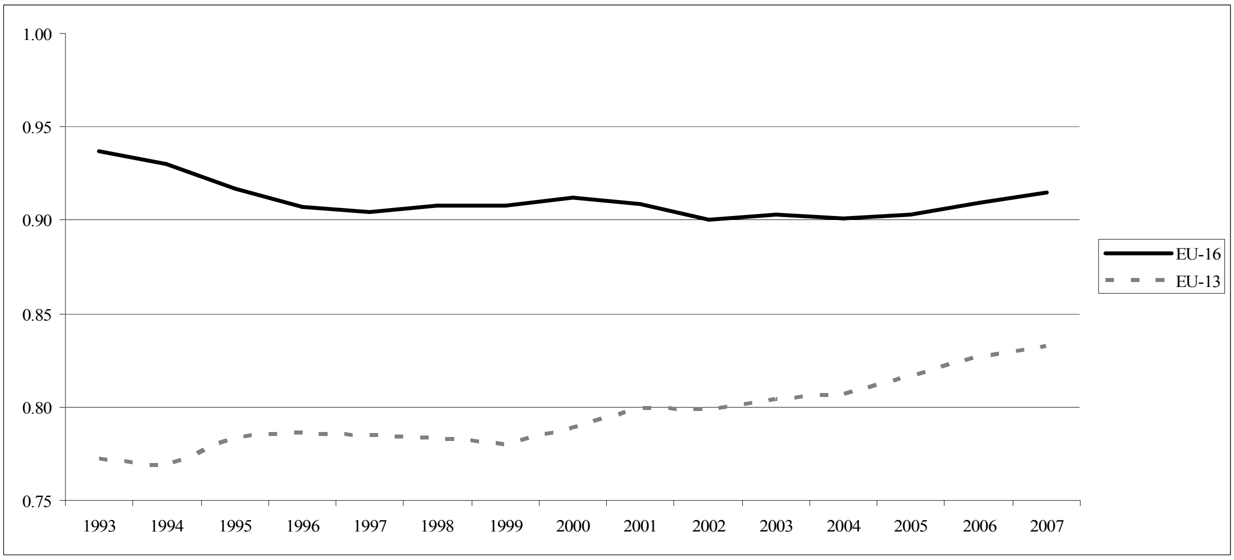
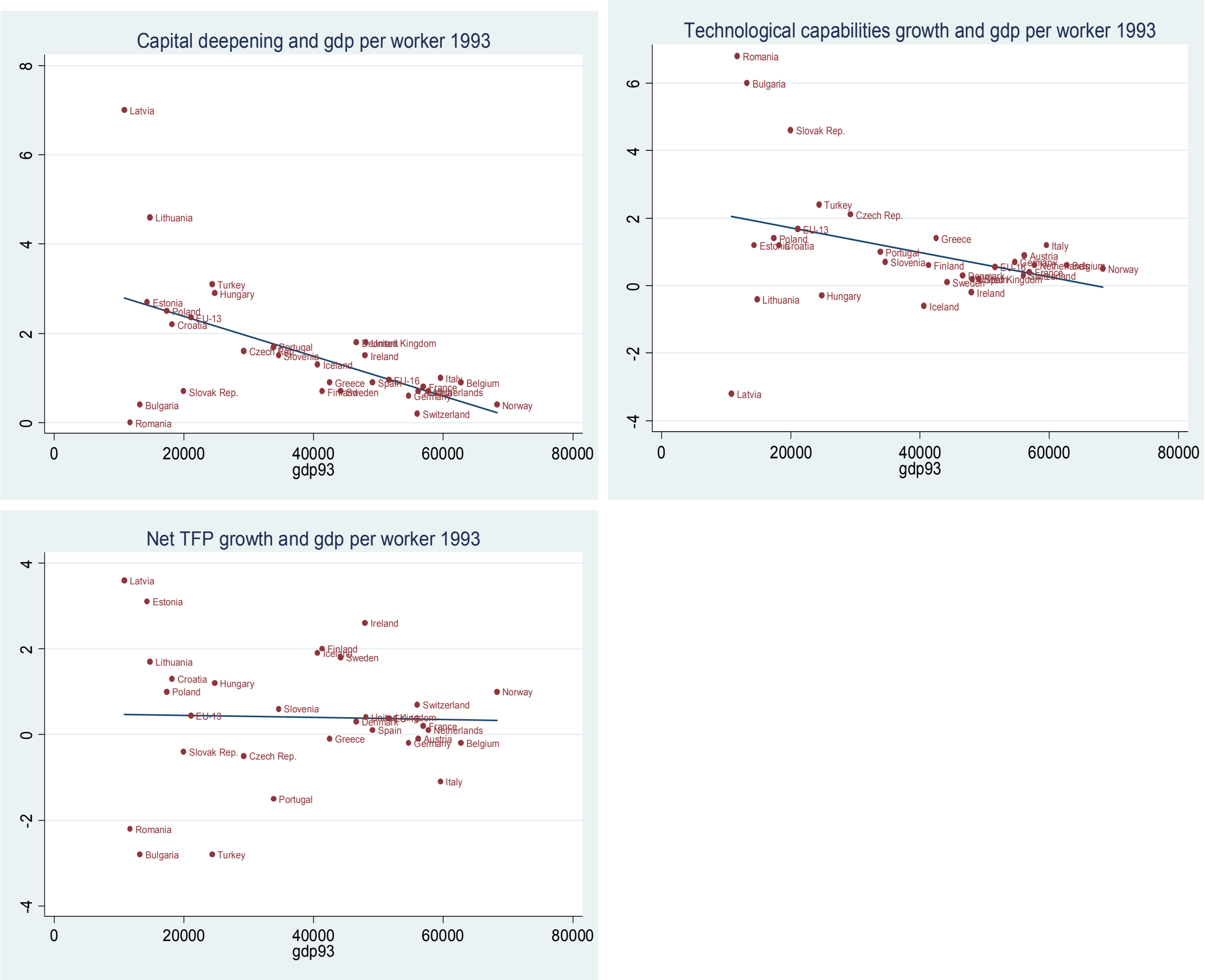


Fig. 7. Labour productivity decomposition: capital deepening, technological capabilities, and net TFP

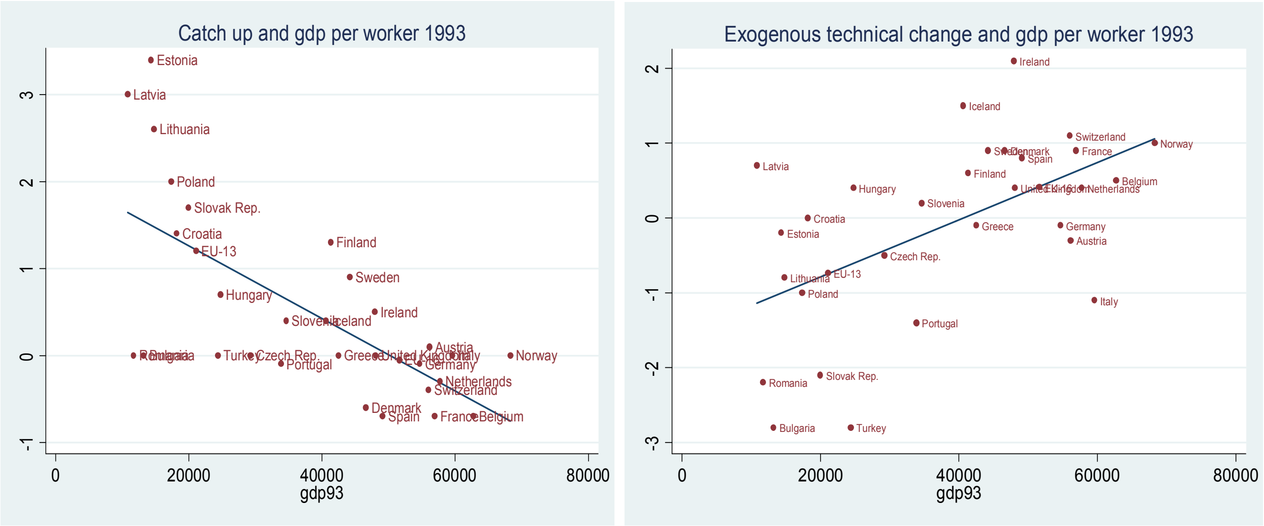


Capital deepening and gdp per worker 1993

Technological capabilities growth and gdp per worker 1993

Net TFP growth and gdp per worker 1993

Fig. 8. Gross TFP decomposition: catch up effect and exogenous technical change



Catch up and gdp per worker 1993

Exogenous technical change and gdp per worker 1993

Table A.1. – Static impact of technological capabilities (equation 5)

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean
Austria	0.93	0.9	0.89	0.88	0.87	0.88	0.87	0.89	0.89	0.86	0.85	0.85	0.84	0.86	0.86	0.87
Belgium	1	0.97	0.95	0.93	0.92	0.92	0.92	0.93	0.92	0.91	0.93	0.95	0.96	0.97	0.98	0.95
Bulgaria	0.45	0.5	0.53	0.48	0.46	0.51	0.57	0.61	0.68	0.68	0.7	0.71	0.73	0.73	0.73	0.6
Croatia	0.74	0.76	0.8	0.81	0.81	0.81	0.81	0.83	0.82	0.81	0.82	0.84	0.85	0.86	0.86	0.82
Czech Rep.	0.62	0.61	0.63	0.64	0.62	0.61	0.61	0.62	0.64	0.64	0.65	0.67	0.7	0.73	0.76	0.65
Denmark	0.99	1	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.99	0.99	0.99	1	0.99
Estonia	0.76	0.75	0.78	0.8	0.82	0.83	0.83	0.85	0.85	0.85	0.86	0.86	0.86	0.87	0.86	0.83
Finland	0.99	0.99	0.98	0.98	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	1	1	1	0.99
France	0.96	0.95	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.95	0.99	0.94	0.95	0.96	0.97	0.96
Germany	0.94	0.93	0.92	0.9	0.89	0.89	0.89	0.88	0.88	0.87	0.87	0.87	0.87	0.88	0.88	0.89
Greece	0.79	0.77	0.75	0.74	0.75	0.75	0.75	0.75	0.77	0.77	0.79	0.79	0.8	0.8	0.8	0.77
Hungary	0.88	0.84	0.84	0.84	0.85	0.85	0.84	0.85	0.85	0.85	0.86	0.87	0.88	0.89	0.9	0.86
Iceland	0.92	0.92	0.92	0.93	0.95	0.96	0.97	0.99	0.99	1	0.98	0.97	0.96	0.93	0.89	0.95
Ireland	0.92	0.91	0.92	0.92	0.94	0.95	0.98	1	1	1	1	1	1	1	1	0.97
Italy	0.94	0.92	0.92	0.89	0.88	0.88	0.87	0.88	0.87	0.85	0.82	0.81	0.8	0.8	0.81	0.86
Latvia	1	1	1	1	1	0.96	0.86	0.82	0.85	0.81	0.77	0.74	0.74	0.75	0.76	0.87
Lithuania	1	1	1	1	1	1	1	1	0.98	0.95	0.93	0.91	0.91	0.92	0.93	0.97
Netherlands	1	1.03	0.97	0.96	0.95	0.96	0.97	0.96	0.94	0.93	0.94	0.94	0.95	0.96	0.97	0.96
Norway	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Poland	0.92	0.89	0.9	0.91	0.9	0.89	0.87	0.88	0.86	0.87	0.89	0.9	0.91	0.94	0.94	0.9
Portugal	0.73	0.69	0.69	0.68	0.67	0.67	0.67	0.66	0.65	0.63	0.62	0.61	0.61	0.62	0.63	0.66
Romania	0.34	0.37	0.4	0.41	0.39	0.38	0.41	0.41	0.46	0.49	0.52	0.54	0.55	0.57	0.58	0.46
Slovak Rep.	0.59	0.57	0.61	0.62	0.61	0.59	0.59	0.6	0.62	0.63	0.66	0.67	0.7	0.73	0.79	0.64
Slovenia	0.82	0.77	0.78	0.78	0.79	0.79	0.78	0.79	0.79	0.8	0.81	0.81	0.82	0.83	0.82	0.8
Spain	0.85	0.89	0.81	0.8	0.79	0.81	0.81	0.81	0.81	0.78	0.79	0.8	0.81	0.82	0.82	0.81
Sweden	1	1	1	1	1	1	1	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.99
Switzerland	0.95	0.93	0.93	0.91	0.91	0.91	0.89	0.9	0.9	0.9	0.9	0.89	0.89	0.91	0.94	0.91
Turkey	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
UK	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mean	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.86	0.86	0.85	0.86	0.86	0.86	0.87	0.88	0.86

Appendix B – DEA linear programs

The previous definitions are still too abstract and we need to operationalize them. A way of doing it is by using the DEA technology. The DEA technology satisfies our previous axioms, thus is a good candidate. Since we deal with a balanced panel dataset, for each time period we can collect all the observed outputs into a Kx1 vector $\mathbf{Y}^t$, all the observed inputs into a Kx2 matrix $\mathbf{X}^t = \left[\mathbf{K}^t, \mathbf{L}^t\right]$ and all the observed external variables into a Kx4 matrix $\mathbf{Z}^t$. The technology set is defined as the convex linear envelope of the data at each point in time (DEA):

$$T\left(\mathbf{X}^t, \mathbf{Y}^t, \mathbf{Z}^t\right) = \left\{\left(y, \mathbf{x}, \mathbf{z}\right) : y \leq \boldsymbol{\lambda}\mathbf{Y}^t, \mathbf{x} \geq \boldsymbol{\lambda}\mathbf{X}^t, \mathbf{z} \geq \boldsymbol{\lambda}\mathbf{Z}^t, \boldsymbol{\lambda} \geq \mathbf{0}\right\}$$

The output distance is calculated using the DEA technology. For every time period the following K linear programs are solved for computing the actual distance functions at each time period for each observation (this means solving KxT linear programs). For every time period the following K linear programs are solved:

$$\begin{aligned} & D_o\left(Y_k^t, K_k^t, L_k^t \mid \mathbf{Z}^t, t\right) = \max \theta \\ & st \quad \theta y_k^t \leq \boldsymbol{\lambda}\mathbf{Y}^t \\ & \qquad \mathbf{x}_k^t \geq \boldsymbol{\lambda}\mathbf{X}^t \qquad\qquad , \quad k = 1, \ldots, K \\ & \qquad \mathbf{z}_k^t \geq \boldsymbol{\lambda}\mathbf{Z}^t \\ & \qquad \boldsymbol{\lambda} \geq \mathbf{0} \end{aligned}$$

We need to compute also mixed period distance functions. The relevant linear programming problems are as follow:

$$\begin{aligned} & D_o\left(Y_k^{t+1}, K_k^{t+1}, L_k^{t+1} \mid \mathbf{Z}^t, t\right) = \max \theta && D_o\left(Y_k^{t+1}, K_k^{t+1}, L_k^{t+1} \mid \mathbf{Z}^{t+1}, t+1\right) = \max \theta \\ & st \quad \theta y_k^{t+1} \leq \boldsymbol{\lambda}\mathbf{Y}^t && st \quad \theta y_k^t \leq \boldsymbol{\lambda}\mathbf{Y}^{t+1} \\ & \qquad \mathbf{x}_k^{t+1} \geq \boldsymbol{\lambda}\mathbf{X}^t \qquad , && \qquad \mathbf{x}_k^t \geq \boldsymbol{\lambda}\mathbf{X}^{t+1} \\ & \qquad \mathbf{z}_k^t \geq \boldsymbol{\lambda}\mathbf{Z}^t && \qquad \mathbf{z}_k^{t+1} \geq \boldsymbol{\lambda}\mathbf{Z}^{t+1} \\ & \qquad \boldsymbol{\lambda} \geq \mathbf{0} && \qquad \boldsymbol{\lambda} \geq \mathbf{0} \end{aligned}$$